

# Scientific research and field applications of polymer flooding in heavy oil recovery

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**Abstract** The heavy oil resources worldwide are estimated at 3,396 billion barrels. With depletion of light oil, we have to face the technical and economical challenges of developing heavy oil fields. Due to severe viscous fingering, the recoveries of heavy oil reservoirs are often below 20% or even 10%. Thermal methods have been successfully applied in many heavy oil fields. However, reservoirs at great depth or thin pay zones are not good candidates for thermal methods.

According to past experiences, polymer flood was not recommended for oil viscosity higher than 100 centipoises. In recent years, polymer flood becomes a promising technology for heavy oil recovery thanks to the widespread use of horizontal wells. This paper highlights the research advances of polymer in heavy oil recovery since 1977. In laboratory tests, polymer achieved tertiary recovery of more than 20% for heavy oil. A few field cases in China, Canada, Turkey, Suriname and Oman are also reviewed and analysed. Some field pilots have shown positive results. Field experiences indicate the major challenge facing polymer flooding effectiveness is to maintain good viscosity of polymer solution.

**KeyWords** Polymer · Oil recovery · Heavy oil · Review

## Introduction

Heavy oil refers to the crude with high density (from 10° to 20° API) and high viscosity (more than 100 cP). Heavy oil

widely exists in many basins around the world, especially in South America, North America and Middle East. The heavy oil resources by region are given in Fig. 1 (Meyer et al. 2007).

Due to high demand for energy and depletion of light oil, we have to investigate technically and economically feasible methods to produce heavy oil. Heavy oil presents great challenges to oil producers. The drastic viscosity difference between heavy oil and water causes injected water to finger through the reservoir, leaving large quantities of oil behind. As a result, recovery of heavy oil was often less than 20% or even less than 10% (Meyer 2003).

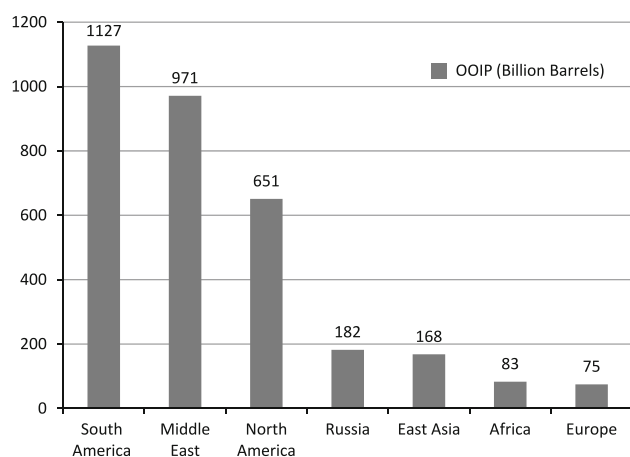
Polymer flood is the most widely used chemical EOR method. By adding polymers to water, the water–oil mobility is lowered. Such a change can lead to better sweep efficiency. It is generally believed that polymer flooding cannot reduce the residual oil saturation, but it can help to reach residual oil saturation in shorter time (Du and Guan 2004).

Polymer flood was proved technically and economically successful in many EOR projects worldwide (Wang et al. 2009; Sheng 2011). In field applications, polymer floods increased recovery by 12–15% (Wang et al. 2002). The field experiences in China showed that polymer flood was cheaper than water flood, due to increased oil output and reduced costs in water injection and treatment (Wang et al. 2003).

Based on past experiences, polymer flood is recommended for oil viscosity less than 100 cP under reservoir temperature, and sandstone reservoir with oil saturation higher than 30%, reservoir permeability greater than 20 mD, net thickness more than 3 m (10 ft), and reservoir temperature less than 90°C or 200°F (Lake et al. 1992; Alkafeef and Zaid 2007; Gao and Towler 2011).

Most commonly used polymers include polyacrylamids (PAM), partially hydrolyzed polyacrylamide (HPAM) and

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**Fig. 1** Heavy oil resources by region

Xanthan. HPAM can be synthesized to high molecular weights and costs less than Xanthan, therefore more popular in field applications. However, HPAM is less tolerant to salt (Morel et al. 2008).

According to a survey, thermal methods such as steam flood and hot water flood are the successful strategy for producing heavy oil (Kootungal 2010). However, thermal methods are not suitable for thin layers and deep reservoirs. Researchers have been studying polymer flood as a possible alternative for such scenarios.

### Advances in scientific research

In 1977, two scientists at Marathon Oil Company pioneered the research on heavy oil recovery with polymer (Knight and Rhudy 1977). Polymer solutions with various PAM concentrations were injected into Ottawa sand packs. The permeability of the sand packs ranged from 3,700 to 5,900 mD. The porosity of the sand packs was around 35%. Two heavy oils were tested. One was a crude oil from Wyoming with viscosity of 220 cP and 19.8°API. The other sample was very viscous synthetic oil (1,140 cP). The mobility ratio with water flood was as high as 30. Polymer flood reduced mobility ratio to 0.34 for the 220 cP oil, and 3.2 for the more viscous crude. Polymer achieved tertiary recovery between 19 and 31%. The results clearly demonstrated the potential of polymer flood in heavy oil EOR.

In recent years, polymer flooding attracted increasing attention in heavy oil recovery, thanks to high oil prices. This topic has been very active in Canada.

In western Canada, Water flood only recovered 10% of the heavy oil reserves. Aiming to improve the heavy oil recovery, researchers tested polymer solution on displacing three oil samples with viscosity of 280, 1,600 and 780 cP (Wassmuth et al. 2007b). The procedure was to inject 0.5 PV (pore volume) of water into high permeability core

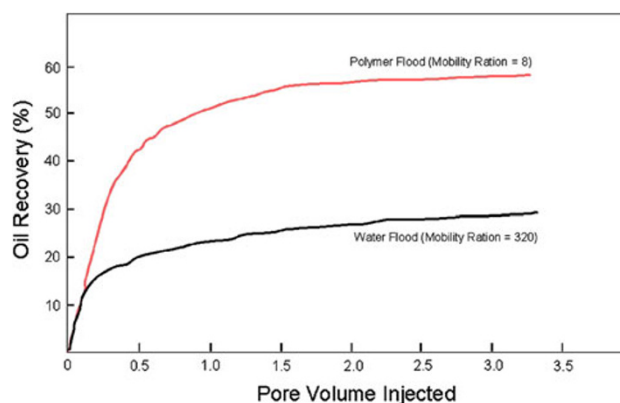
until water cut reached 90%. Afterwards, 6 PV of polymer solution was injected into the core, followed by 5 PV of water. The tested polymer concentration was 1,500 ppm, which produced an in situ viscosity of 18 cP. The incremental recovery was 16, 22 and 23% for the three oil samples, respectively. The test result in Fig. 2 clearly shows the acceleration of recovery process with polymer flood.

At University of Regina, HPAM solution was tested on homogeneous and heterogeneous sand packs (Wang and Dong 2007). The viscosity of test oil was 1,450 cP at room temperature of 22.5°C. The homogeneous sand had porosity of 0.35 and permeability of 7 Darcy. The sand pack was first flooded with water till oil recovery of 42%, and polymer solution was subsequently injected. The tertiary recoveries ranged from 4% with polymer solution of medium viscosity, to 19% with high-viscosity polymer solution.

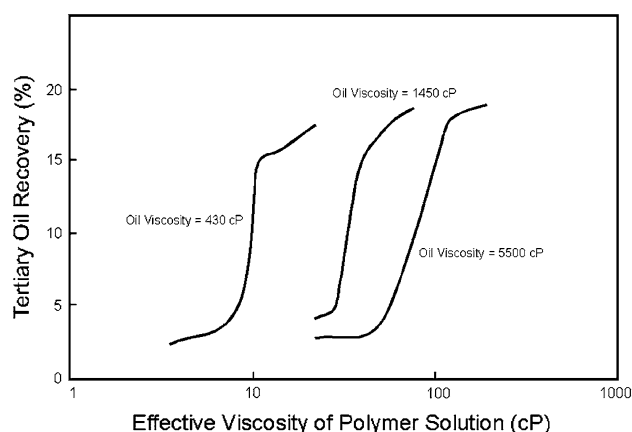
In a lab study in Alberta, 0.5 PV of polymer injection lead to 20% of tertiary heavy oil recovery. The tested crude had a viscosity of 600–2,000 cP and a gravity of 14°API. The injected polymer solution produced a viscosity of 25 cP (Wassmuth et al. 2007a).

In another research project, PAM solutions of various concentrations of 500, 1,000, 5,000 and 10,000 ppm were tested against a heavy oil sample with viscosity of 1,450 cP (Asghari and Nakutnyy, 2008). The test media were two sand packs with permeability of 2 and 13 Darcy. It was discovered that polymer concentration must exceed 5,000 ppm to mobilize the test oil.

At University of Calgary, heavy oil samples with viscosities ranging from 430 to 5,500 cP were flooded with polymer solutions with effective viscosities of 3.6–359.3 cP. It was discovered that the polymer solution must exceed certain effective viscosity to achieve a tertiary recovery of more than 10%. This can be seen in Fig. 3 (Wang and Dong 2009).



**Fig. 2** Comparison of water flood and polymer flood on 1600 cP oil



**Fig. 3** Higher polymer viscosity lead to higher oil recovery

The influence of oil saturation was also tested. The sand pack was flooded till oil recovery of 35%, and polymer flood was then initiated. It was discovered that polymer solution with relatively low viscosity achieved good tertiary recovery between 8 and 21%. This indicated that polymer flood could be more effective when applied early. The tests on heterogeneous sand pack lead to much lower tertiary recovery, compared with the results for homogeneous sands.

The heavy oil reservoirs in Saskatchewan are not suitable for thermal methods or miscible  $\text{CO}_2$  flood. At Saskatchewan Research Council, polymer flood was tested on heavy oil recovery (Zhang et al. 2010). The heavy oil had a gravity of  $18.3^\circ\text{API}$  and a viscosity of 707 cP at  $15^\circ\text{C}$ . The molecular weight of the test polymer was 8–20 million. The polymer solution was prepared by adding 0.4 wt% of polymer to brine, which produced a viscosity of 29 cP. Firstly, 4.7 PV of water was injected into the sand pack with a permeability of 2.35 Darcy. Subsequently, 0.8 PV of polymer solution followed, and finally chased by 2.85 PV of water flood. The polymer flood recovered 13% of extra oil after initial water flood. The test data are reproduced in Fig. 4.

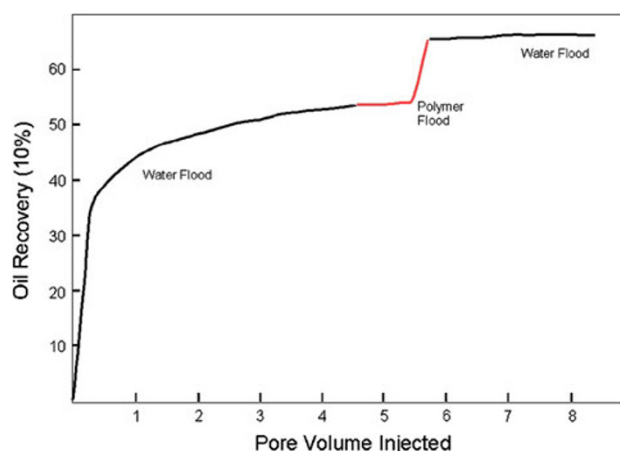
For the laboratory research surveyed here, polymer flood could lead to tertiary oil recovery of more than 10%. However, high polymer concentration and viscosity were required to mobilize heavy oil.

### Field applications

Even though laboratory research demonstrated the potential of polymer flood in recovering heavy oil, most oil companies are still reluctant to apply this technology in the field. Five field cases are identified and reviewed here.

#### Bohai Bay, offshore China

It was estimated that more than 70% of the reserves in Bohai Bay is heavy oil (Zhou et al. 2008). The recovery by



**Fig. 4** Oil Recovery with water flooding followed by polymer flooding

10 years of water flooding was only 13.5%. China National Offshore Oil Company (CNOOC) started polymer flood in Bohai offshore field since 2002 (Liu et al. 2010). The pilot test on a single well lasted 500 days. The water cut dropped from 95 to 54%. The incremental oil was  $2,5000 \text{ m}^3$  (157,250 bbl).

After the success of the single well treatment, polymer was injected to four injection wells with six corresponding production wells. The reservoir depth was 1,300–1,600 m, and the average thickness of pay zone was 61.5 m. The sands were poorly consolidated with porosity of 28–35%, and average permeability of 2,600 mD (Han et al. 2006). The reservoir temperature was about  $65^\circ\text{C}$ . The average well spacing was 370 m. The water cut after polymer flood reduced by 10%, and  $17,700 \text{ m}^3$  (111,330 bbl) of incremental oil per well was produced. Till 2010, totally 53 operations of polymer flood have been conducted and the incremental oil was about  $636,000 \text{ m}^3$  (4 MMSTB).

#### East bodo reservoir, Alberta Canada

The East Bodo sandstone reservoir is located in Alberta and Saskatchewan in Canada. The reservoir had good permeability (1,000 mD) and oil viscosity was high (600–2,000 cP). The polymer injection with horizontal wells was initiated in May 2006. The major challenge was the quality of source water for mixing polymer solutions. At the early stage, the maximum polymer viscosity produced was only 10 cP at 1500 ppm of polymer concentration. No pressure resistance was observed. Later, the water supply was changed to a fresher water source, and the polymer solution achieved a much higher viscosity of 60 cP. The wellhead pressure increased to 6,000 kPa (870 psi) at injection rate of  $200 \text{ m}^3/\text{day}$  (1,258 bbl/day). The production data after polymer flooding was not reported (Wassmuth et al. 2009).

### Tambaredjo field, Suriname

The pilot was a sandstone reservoir at 387 m (1,270 ft) with pressure of 1,724 kPa (250 psi). The net pay zone was 6.7 m (22 ft) thick with porosity of 33% and permeability of 3–6 Darcy. The live oil viscosity was 400 cP at reservoir temperature 36°C (97°F). Polymer flood started in September 2008. The polymer concentration in the injected fluid was 1000 ppm, which produced a viscosity of 44–60 cP. The polymer injection rate was about 32 m<sup>3</sup>/day (200 bbl/day), which was 7–10 times less than previous water injection rate.

Till 2010, totally 0.22 PV of the well pattern has been injected. Polymer breakthrough occurred at two of the five-spot wells after approximately 1 year of injection. Analysis of polymer fluid revealed 7% viscosity reduction from mixing tank to wellhead. It was thus estimated that 40% of polymer viscosity was already lost before entering formation rock. The production response to polymer flood was not reported (Manichand et al. 2010).

### Turkey case study

Bati Raman was a heavy oil field located in southeast Turkey with oil gravity of 10–15°API. Primary recovery was only 1.5%, and CO<sub>2</sub> flooding improved recovery up to 5%. Polymer solution was injected to improve the sweep efficiency of CO<sub>2</sub>. Three injection wells took 10,000 barrels of polymer solution each, and pressure increases were observed. After injection was complete, the wells were shut in for a week, and CO<sub>2</sub> injection resumed. Increased production was observed in 16 production wells after 3 months of injection. The total cost of the polymer treatment was USD 445,000. The payout time was 1 year (Topguder 2010).

### Oman case study

The Marmul Field in southern Oman was discovered in 1956 and brought on stream in 1980. The OOIP was estimated at 390 million m<sup>3</sup> (2,453 MMSTB). Like many fields in the southern Oman, Marmul was characterised by heavy, viscous crude oil that was difficult to extract.

The Kalata formation of Marmul field was located at 610 m (2,001 ft) deep with reservoir temperature of 46°C (115°F). The oil is medium heavy with reservoir viscosity of 80–110 cP. It was considered a good candidate for polymer flood.

The first small-scale polymer flood pilot took place between 1986 and 1988, with one injector well and four producing Wells. The OOIP of the block was estimated at 190,000 m<sup>3</sup> (1,195 MSTB). PAM solution of 1,000 ppm was injected at a flow rate of 500 m<sup>3</sup>/day (3,145 barrel/

day). The polymer solution gave a viscosity of 15 cP at surface under 46°C (115°F).

From May 1986 to September 1986, a water pre-flush of 0.23 PV was injected. A polymer slug of 0.63 PV followed till August 1987. A water post flush of 0.34 PV was completed in January 1988. The recovery was 12% at the end of water pre-flush, 46% at the end of polymer flood, and 59% at the end of the post flush (Koning et al. 1988).

Because of discoveries in Oman that promised cheaper extraction costs than the tough Marmul field, the Marmul polymer project was shelved. Today's economic conditions make the various EOR techniques more feasible. Recently petroleum development Oman (PDO) announced the start of a large-scale polymer flood project in southern Oman. PDO estimated that by using polymer flooding it could raise the total percentage of oil recovered from the reservoir to the high 20 s or even low 30 s.

### Challenges facing polymer flooding operations

Polymer flood will be more effective if applied early, when oil saturation is well above residual oil saturation. The major challenge in polymer flood operations is to maintain a good polymer viscosity. Water salinity, shear degradation, thermal degradation and adsorption can severely damage viscosity of polymer fluid. Other issues facing field applications included low injectivity, low productivity, and polymer plugging formations (Thomas 2008).

At Daqing field in China, a field test was performed in 1998 to investigate the effect of water salinity. Waste water with salinity of 3,800 ppm was used to prepare polymer solution. The test was conducted in a 395-acre block with 45 wells and OOIP of 4.45 million m<sup>3</sup> (28 MMSTB). The tertiary recovery was much lower compared to adjacent areas flooded with less saline water (Wang et al. 2002).

For offshore fields, sea water is usually available for preparing polymer solution. Test data from Dalia field offshore Angola showed that PAM viscosity decreased rapidly with increase in water salinity. Moreover, shearing at the wellhead chokes caused 25–50% of loss in polymer viscosity (Morel et al. 2008).

Existence of oxygen in polymer solution can severely degrade polymer viscosity. Therefore, oxygen must be removed from the polymer solution. Polymers become unstable at high temperature. Most field applications of polymer flooding were under reservoir temperatures of less than 75°C (Du and Guan 2004).

At Daqing field in China, injection wells suffered from high injection pressure and low injection rate. Fracturing could only improve injectivity for less than 3 months. Improved fracturing technology with resin-coated proppant



enhanced well injectivity for up to 26 months (Wang et al. 2008).

The low permeability zones at the production wells were also fractured to increase flow rate and recovery (Wang et al. 2002). For example, 66 production wells were fractured. After the treatments, the average fluid production rate per well increased by 41%, and the average oil production rate per well increased by 46%.

High polymer viscosity can improve conformance and recovery. But polymer with too high molecular weight can plug pore faces (Wang et al. 2002). In a field test, polymer with molecular weight of 17 million plugged formations with permeability ranging from 100–200 mD. But the same polymer did not plug another reservoir with higher permeability.

Polymer flood in offshore fields faces more challenges than that onshore (Raney et al. 2011). These challenges include costs to transport chemicals, space for mixing facilities on platform, large well spacing, and reduced polymer viscosity when mixed with sea water.

In recent years, some operating companies started to seriously consider EOR methods for offshore fields (Bondor et al. 2005). For example, the Dalia field, 130 km offshore Angola at water depth of 1,300 m (4,265 ft), started to undergo polymer flood since February 2010 (Morel et al. 2010).

## Conclusions

Past laboratory research showed that polymer could increase heavy oil recovery by more than 20%. Field cases in China, Turkey and Oman demonstrated the success of polymer flooding in heavy oil fields.

In field applications, the major challenge is to maintain polymer viscosity in surface injection facilities and under reservoir conditions. Low salinity water should be used to mix polymer solutions. Surface injection facilities should be carefully designed to minimize shearing degradation.

It can be concluded that polymer flood is a promising technology for recovering heavy oil. However, higher polymer concentration will be required to mobilize heavy oil. As a result, the cost of polymer will be significantly higher when polymer flood is applied in heavy oil fields.

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